Construction and Verification of a Wasatch Front Community Velocity Model: Collaborative Research with San Diego State University and the University of Utah

Final Technical Report

Harold Magistrale
Kim Olsen
San Diego State University

Jim Pechmann
University of Utah

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Introduction. A fundamental problem in assessing seismic hazard from an active fault zone is determining the distribution, amplitude, frequency characteristics, and duration of strong ground motion from potential future earthquakes. This task becomes more difficult when accounting for the influence of 3D geologic structures, such as sediment-filled basins. The population of Utah is concentrated in such basins at the foot of the Wasatch Front, with 40% of the population residing in the Salt Lake basin. The Wasatch Front is formed by the active, normal Wasatch fault, the most prominent potential source of future large earthquakes in the area.

Evaluation of the seismic hazard requires numerical ground motion simulations to quantify the contribution of deep basin structure and shallow site conditions to ground motions. A key requirement to perform these simulations is the availabilty of a 3D Wasatch Front community seismic velocity model (CVM). With NEHRP support we have developed an initial version of the community velocity model. The CVM has been developed in consultation with the Utah Ground-Shaking Working Group (UGSWG), a NEHRP-supported effort spearheaded by the Utah Geological Survey (UGS).

CVM Construction Method. In creating the Wasatch Front CVM, we followed the method that Magistrale et al. (2000) used to construct the SCEC southern California CVM. Both models consist of detailed, rule-based representations of the major populated sediment-filled basins, embedded in a 3D crust, over a variable depth Moho, over upper mantle velocities. The basins are parameterized as a set of objects and rules implemented in a computer code that generates seismic velocities and density at any desired point. The objects are stratigraphic surfaces constructed from geological, geophysical, and geotechnical data, and the rule is Faust's relation $Vp = k(da)^{1/6}$ where Vp is P-wave velocity, d is the maximum depth of burial of the sediments, a is the sediment age, and k is a constant. Age at any point in a basin can be interpolated from the surfaces. The constant k is calibrated for each surface by comparison to well sonic logs and seismic refraction surveys. Density is derived from Vp using a standard relation; density is used to find Poisson's ratio and Vs is calculated from the Vp and Poisson's ratio. The method is flexible: for example, in the Salton trough in southern California the basin objects are isovelocity surfaces defined from seismic refraction results, and the rule is a simple interpolation of the seismic velocities.

The shallow basin velocities are directly constrained by geotechnical borehole logs and detailed surface site response unit mapping based on surface geology and Vs30 measurements. If queried at a borehole location, the model returns the original borehole measurement; if the query is away from a borehole, the model returns a value that is a weighted sum of nearby boreholes and a mean velocity profile of that site response type.

This parameterization is convenient to store, transfer, and update as new information and verification results become available. Model elements can be added, modified, or removed. Model element registration is achieved by careful digitization and mutual consistency checks.

The Wasatch Front CVM. The area covered by the current Wasatch Front CVM encompasses the Salt Lake City-Ogden-Provo urban corridor within which more than 75% of the population of Utah resides (Figure 1). The boundaries of the CVM were selected to match the boundaries of the area for which UGS geologists have developed maps of unconsolidated sediment thicknesses and detailed Vs30-based site response units (see Ashland, 2001; Wong et al., 2002; Solomon et al., 2004; and Bay et al., 2005). This area includes the Salt Lake basin, the

Weber and Cache basins to the north, and the Utah basin to the south. The Salt Lake, Weber, and Utah basins bound three central, active segments of the Wasatch fault (Figure 1). The Salt Lake basin has the most data available.

The construction and enhancements of the Wasatch Front CVM proceed in consultation with the UGSWG to ensure all usable data are identified and to make sure the CVM meets the needs of potential users. The Wasatch Front CVM (Figures 2, 3) is available as a computer code, to be downloaded and run locally. The model provides a user-friendly and objective gateway to extract subsurface elastic parameters that may be used in linear and nonlinear 1D, 2D, and 3D ground motion calculations for seismic hazard analyses. It provides an appropriate starting model for perturbation studies, such as linearized inversions of travel times for crustal velocities. It will be hosted on the UGS website.

Basin Representations. The Salt Lake basin geometry is characterized by the depths to the interface between unconsolidated and semi-consolidated sediments (known as R1), the interface between the semi-consolidated and consolidated sediments (R2), and the depth to basement (R3) (Hill et al., 1990). These interfaces are used as reference surfaces in all the model basins.

R3 (depth to basement) was defined in all basins by compiling the gravity study of Mabey (1992), the Salt Lake basin refraction profile of Bashore (1982), the seismic reflection lines and gravity data in western Davis and Weber basin of McNeil and Smith (1992), the Salt Lake basin gravity study of Mattick (1970), and the depth to basement found in 97 wells compiled by the UGS (UGS, 2005). The contact between the basin sediments and the bedrock outcrop marks the zero-depth contour of R3 (and likewise R1 and R2). This contact is digitized from the geologic maps of Moore and Sorensen (1979), Doelling et al. (1980), Davis (1983a,b, 1985), Pampeyan (1989), Witkind and Weiss (1991), and Dover (1995).

R2 has been identified only in the Salt Lake Valley basin (Hill et al. 1990; Radkins, 1990). Radkins (1990) performed gravity modeling with constraints from 40 well logs and three seismic reflection lines to map the R2 interface depth. To construct R2 in the other model basins we use the average ratio of the R2/R3 depths in the Salt Lake basin and define R2 elsewhere as that fraction of R3.

The R1 depths in Salt Lake Valley basin are constrained by 125 well logs compiled by Arnow et al. (1970). R1 in the other basins is defined by water well data compiled by Wong et al. (2002) and Solomon et al. (2004). To construct R1 in the parts of the basins outside the latter compilations, we use the average ratio of the R1/R3 depths calculated where R1 is well defined and define R1 elsewhere as that fraction of R3.

The k and nominal age of the reference surfaces used in the Faust relation were calibrated by trial and error to the deep Vp well logs presented in Radkins et al. (1989). Those logs show the material between R2 and R3 as having velocities typical of well-lithified sedimentary rock, near the velocities of the crystalline rock basement below R3. Thus, in the initial CVM, R2 was identified as basement (Figure 2). We are currently analyzing trial waveform modeling and additional data sources that suggest seismic velocities less than that of crystalline basement rock should be installed between R2 and R3.

The initial versions of the R2 and R3 surfaces were modified to reflect the surmised control of the Wasatch fault zone on the configuration of the east side of the basins. We use the detailed fault zone attitudes of Bruhn et al. (1990) in the Salt Lake basin; elsewhere we use a dip of 50 degrees.

Geotechnical Layer. McDonald and Case (2005) have compiled a database of shallow Vs and other geophysical observations in the Salt Lake basin. Near-surface seismic velocities in the Salt Lake basin come from 22 Vp and Vs borehole logs to about 55 m depth published by Tinsley et al. (1991) and Williams et al. (1993), Vs logs of geotechnical boreholes (≤ 90 m deep), and surface wave studies by Schuster and Sun (1993; 28 sites, Vs to 40 m depth) and Bay et al. (2004, 2005; 45 sites, Vs to 30-60 m depth). Williams and Stephenson (2007) and Wilder and Stoke (2007) obtained relatively deep (to a few hundred meters) additional Vp and Vs profiles, respectively, in the Salt Lake and Utah basins. These latter data were included in a model revision funded by the UGS. McDonald (pers. comm., 2006) has organized all these data in a consistent format.

Ashland and Rollins (1999), Ashland (2001), Ashland and McDonald (2003) and Bay et al. (2005) defined and mapped soil site response units based on grain size and Vs30 measurements. McDonald and Bay (2008) have updated the site response map as new shallow Vs data have become available. The model extends the surface site response units to the base of the unconsolidated sediments (R1).

The shallow Vs data is sorted in the CVM by basin and site response unit. If queried for a shallow value, the model determines the specific basin and the site response unit, and returns a value that is a weighted sum of nearby boreholes in the same site response unit in the same basin and a mean velocity profile of that unit. In areas of the CVM not covered by the site response map, the model uses a generic velocity depth profile of the most common response unit. In the geotechnical layer, Vs is obtained directly from the shallow borehole data, and Vp is derived from Vs using the relation of Castagna et al. (1985).

Crustal Velocities. The sub-basin crustal velocities are taken from the regional 3D crustal tomography results of local earthquake travel times by Lynch (1999). Where that study lacks resolution (due to sparse raypath coverage), we insert the standard 1D model used by the University of Utah Seismological Station for earthquake location (Pechmann, pers. comm., 2005), scaled to fit into the crustal thickness determined by Loeb (1986) and Loeb and Pechmann (1987). The crustal Vp is defined on a regular 3D mesh. If the depth of a point of interest is below the bottom of the basins, its velocities are determined by interpolation from the nearest 8 crustal mesh points. Vs is found from Vp using a fixed Vp/Vs ratio of 1.74.

Moho and Upper Mantle. Moho attitude and upper mantle velocities are taken from the analysis of regional earthquake travel times by Loeb (1986) and Loeb and Pechmann (1987). In the Wasatch Front CVM, the Moho is defined by seismic velocity instead of using an actual surface, as in the southern California CVM. The lowermost crustal and upper mantle velocities are defined on the same mesh as the crustal velocities, as above.

Validation of the CVM. The construction of the Wasatch Front CVM is coupled to a concurrent effort test the CVM by finite difference waveform modeling of three-component ground motion data for local events recorded on the University of Utah seismic network within the model boundaries. This work is ongoing. The modeling results suggest where refinements are needed in the model.

We have compared long-period (0.5-1.0 Hz) synthetics generated in the assembled Wasatch Front CVM to data recorded for two small earthquakes in the model area. These two earthquakes (the 'Magna' and 'Lehi' events) were found suited for validation studies based on the signal-to-noise ratio of the recordings. The 0.5 Hz lower frequency cut-off is dictated by the noise in the records, and the 1.0 Hz upper frequency cut-off is imposed by computational limitations. The focal mechanism and magnitude for the two events were based on a combination of waveform inversion and moment tensor inversion from the available seismic records (Table 1). The simulations (Table 2) were carried out on the Teragrid supercomputer clusters Datastar and Blue Gene at the San Diego Supercomputer Center, and the linux cluster Babieca at San Diego State University, using 150-400 processors.

Table 1. Focal parameters for the two validation events

Events	M	Hypocentral depth (km)	Epicenter location	Strike (^{o})	Dip (^{o})	Rake (^{o})
2001/07/08 'Magna'	3.52	11.6	40.7422N, -112.0673E	168	52	-66
2001/05/24 'Lehi'	3.30	8.9	40.3727N, -111.9312N	131	70	-155

Table 2. Numerical parameters for the validations

Simulation time (sec)	60
Time step (sec)	0.0024
Grid spacing (m)	40
Minimum Vs (m/s)	200
Magna event model dimensions	35 km x 32 km x 13 km
Lehi event model dimensions	39 km x 54 km x 13 km

Currently, the Wasatch Front CVM does not contain hardwired Q values. Both events were simulated assuming the Qs-Vs relation from Brocher (2006):

$Qs=13$ ($Vs<0.3$ km/s)

$Qs=-16. + 104.13 * Vs - 25.222 * Vs^2 + 8.2184 * Vs^3$ ($Vs \geq 0.3$ km/s)

$Qp=2 * Qs$

Future validation runs (carried out as part of NEHRP award number 06HQGR0206, PIs Olsen and Pechmann), will explore the effects of alternative Q models based on the fit between synthetic and recorded ground motions.

Figures 4 and 6 are maps of the location of the Magna and Lehi events, respectively, and the stations used for comparison of synthetics and data. The validations are shown in Figures 5 and 7. The best fit is obtained for the Magna event.

The 0.5-1.0 Hz synthetic and recorded waveforms for the Magna event show a variable but in general good fit. Some components at some sites, i.e., the horizontal components for ICF and NOQ are well matched. The 0.5-1.0Hz peak ground velocities (PGVs) for the synthetics are generally within a factor of two of those for the data. An exception here is the rock site CTU, where the synthetics overpredict the recorded PGVs. A reduction in the magnitude to about M3.3 improves the fit at CTU but worsens the fit at the remaining stations. The durations are typically underpredicted by up to a factor of two at basin sites (e.g., SCC, JRP and LGC). The underprediction of the recorded duration at the shallow soil site UUE may be caused by effects from the building hosting the seismic instrument.

The fit between 0.5-1.0 Hz synthetic and recorded waveforms for the Lehi event is generally worse than that for the Magna event. This is in part due to a smaller signal-to-noise ratio for most stations available for the Lehi event (only 'yellow' site quality, indicating intermediate signal-to-noise ratio in Figure 6). It is possible that the degraded fit for Lehi compared to that for the Magna event is also a result of less constraints on the CVM outside the Salt Lake Valley. Finally, the source mechanism and magnitude for the Lehi event are less well constrained as compared to those for the Magna event. The best fit is found for the horizontal components for CTU and the N component for NOQ which are reasonably well matched for the first ~20 s of waves. The durations are generally underpredicted by a factor of two or more.

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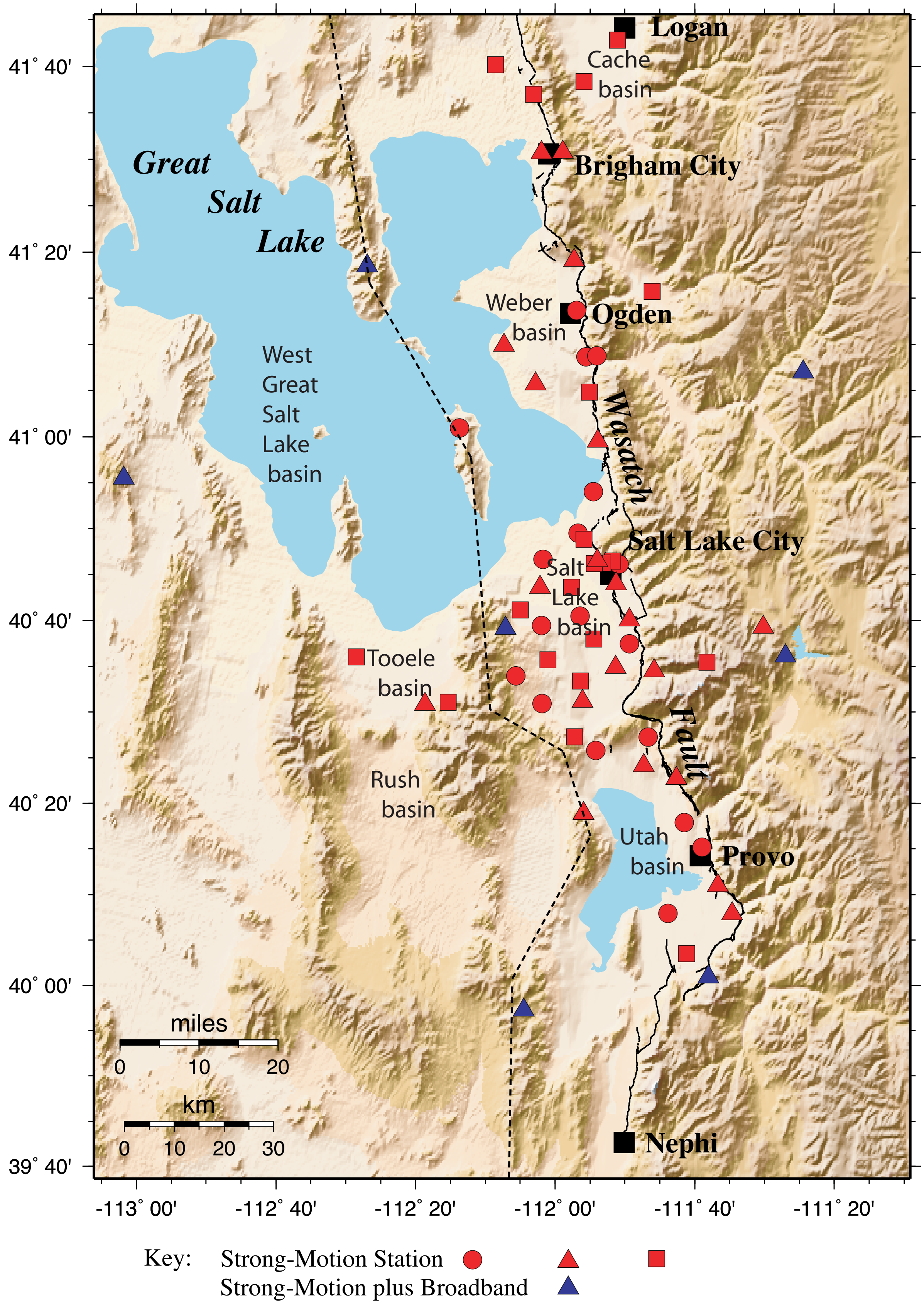

Figure 1. The Wasatch Front CVM model area. Basins east of the black dashed line are included in the current model version. Red and blue circles, triangles, and squares indicate elements of the University of Utah seismic network.

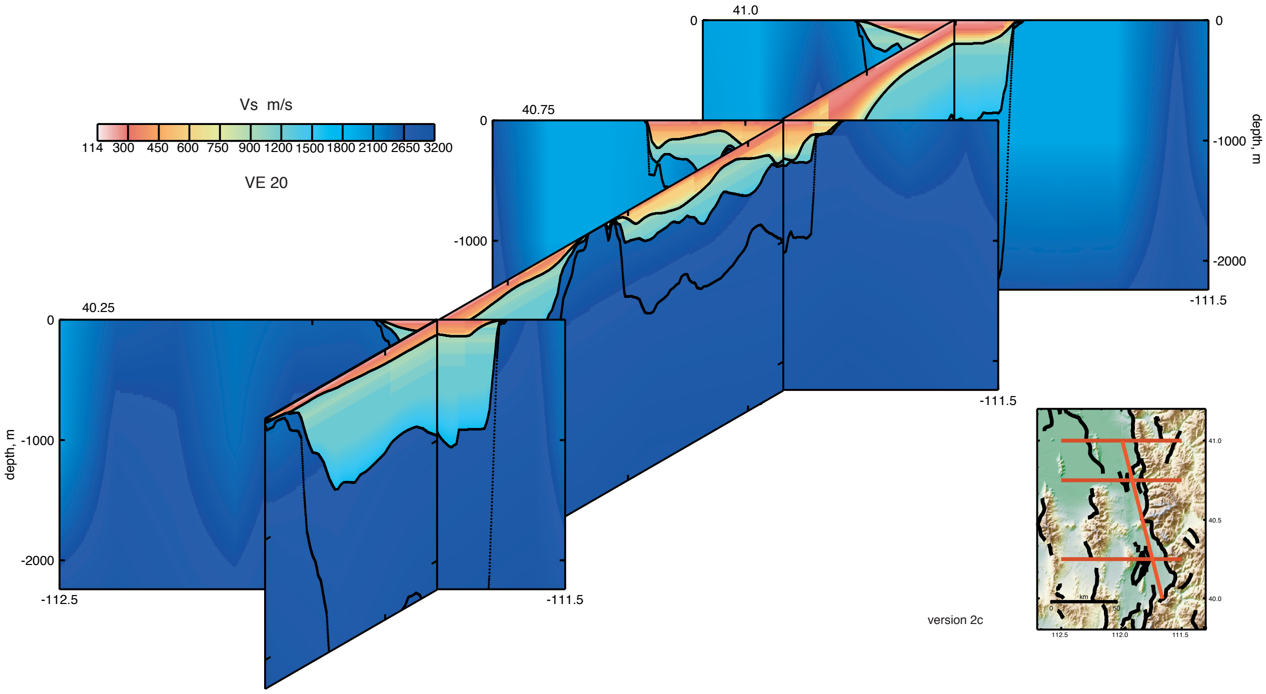

Figure 2. Fence diagram of Vs (see color scale) along the Wasatch Front from the current CVM. Red lines on index map show fence panel locations. Black lines indicate, from top to bottom, R1, R2, and R3 (see text, some of the R3 line goes of the bottom of the panels).

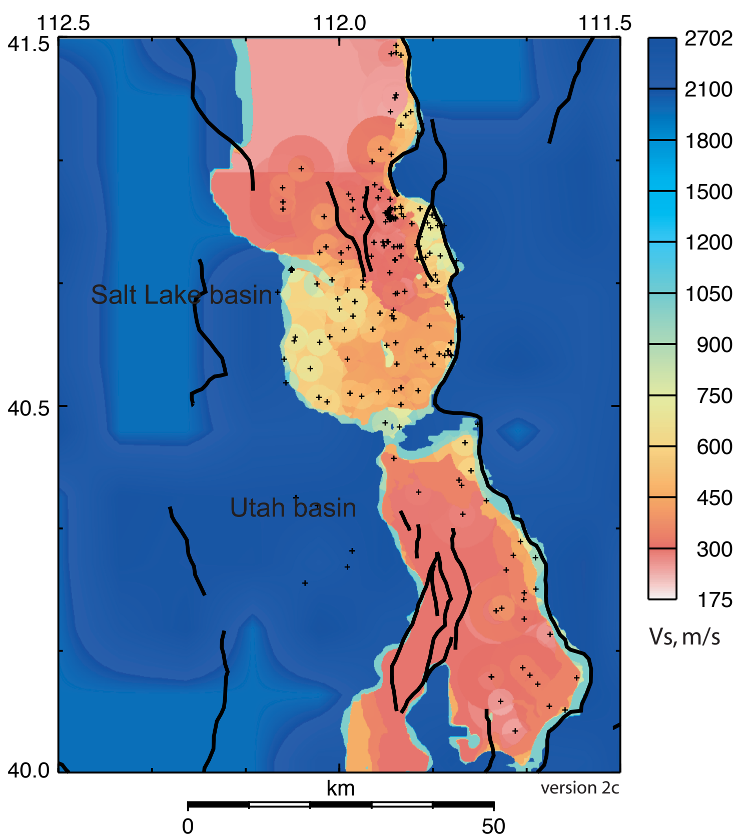

Figure 3. Map of Vs (see color scale) at 30 m depth. Crosses indicate borehole locations.

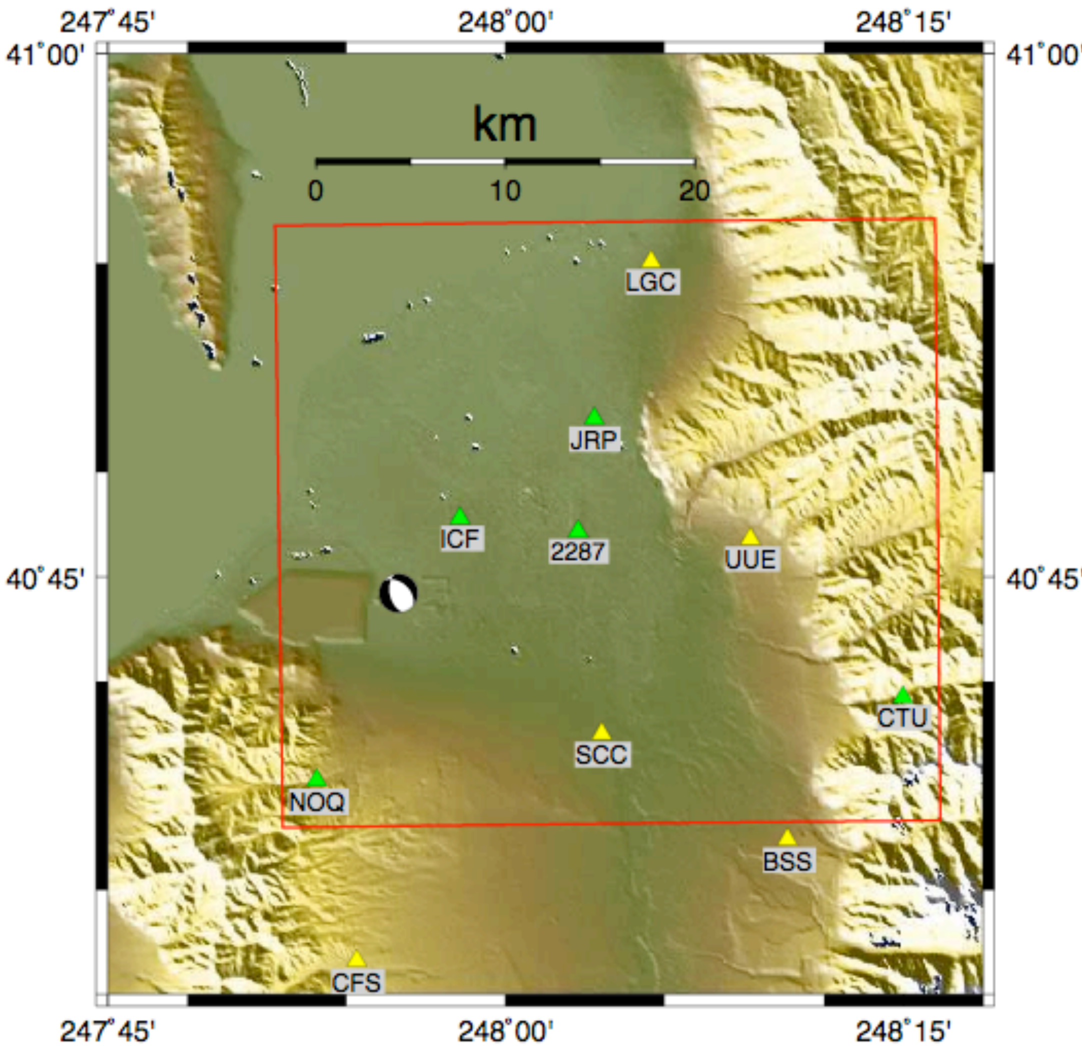

Figure 4. Topographic map showing the epicentral location and focal mechanism of the Mw3.52 010708 ('Magna') event with stations (triangles) used for comparison between synthetics and recorded seismograms. Green triangles depict stations in the category of the highest signal-to-noise ratio, and yellow stations depict stations with intermediate signal-to-noise ratio. The red rectangle depicts the area of the computational model.

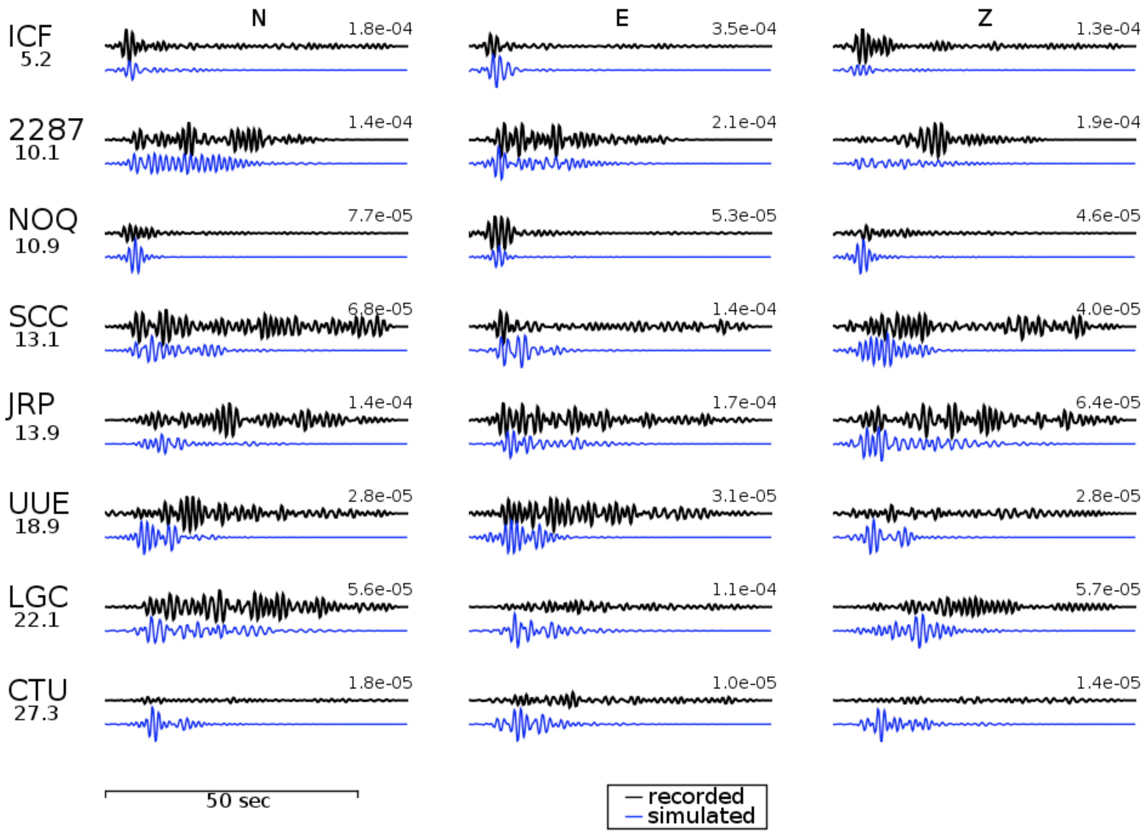

Figure 5. Comparison of 0.5-1.0 Hz velocity synthetics (blue) compared to data for the Mw3.52 010708 ('Magna') event.

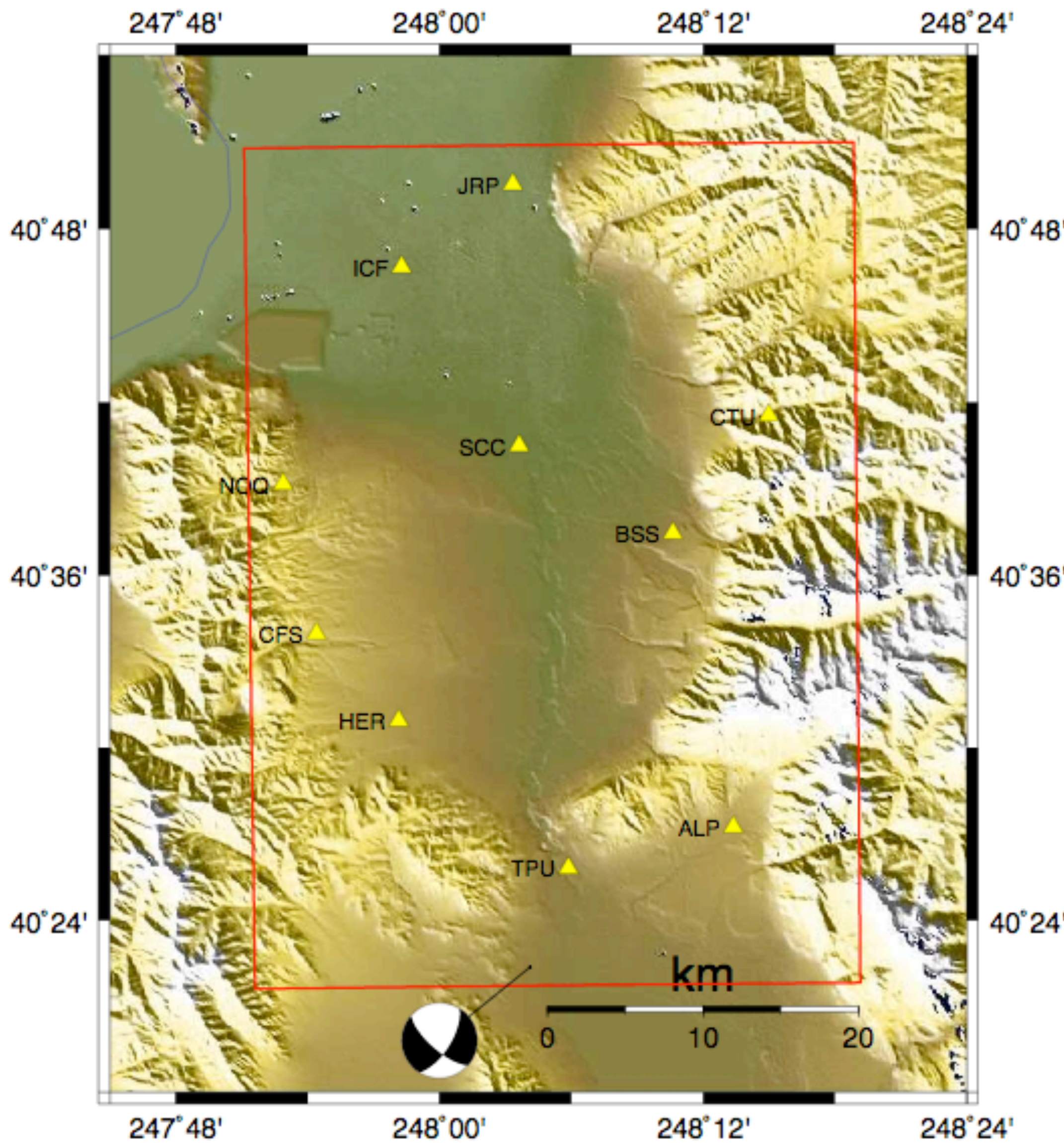

Figure 6. Map showing the epicentral location and focal mechanism of the Mw3.30 010524 ('Lehi') event with stations (triangles) used for comparison between synthetics and recorded seismograms. All stations are in the category of intermediate signal-to-noise ratio. The red rectangle depicts the area of the computational model.

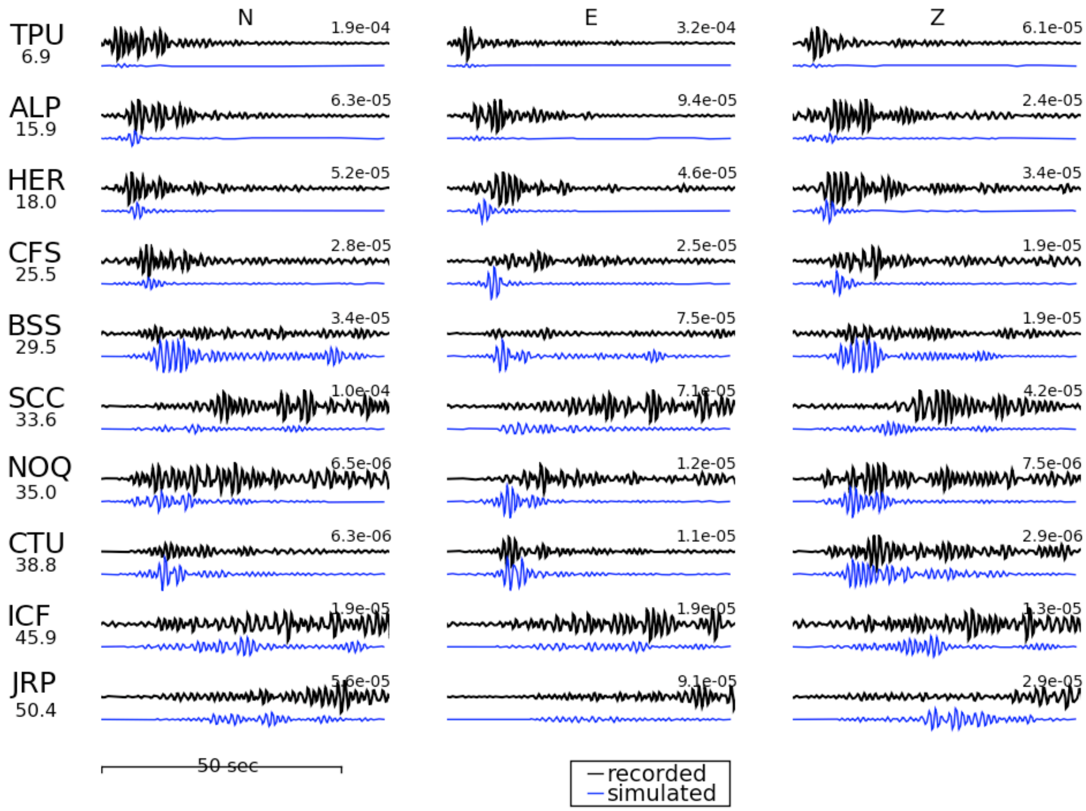

Figure 7. Comparison of 0.5-1.0 Hz velocity synthetics (blue) compared to data for the Mw3.30 010524 ('Lehi') event.